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13. ABSTRACT (Maximum 200 words)

Alkali Metal Thermal to Electric Conversion (AMTEC) technology converts the heat from virtually any combustible fuel directly to electric power. This technology has the potential to be very efficient, even at low power levels. This Phase 1 program set the path for AMTEC generator development to meet the Palm Power program goals of a 20 W system with a specific energy density (including the fuel) of 3000 W-hr/kg for a 10 day mission. The first prototype generator was developed, and incorporated into the first complete fuel fired AMTEC system. This generator is relatively large, compared to the Palm Power goal, but was intended to allow the development team to identify and work through key system level integration issues, while at the same time working the more basic technology issues that can lead to a compact system. The overall system was designed and separate system elements tested prior to the final assembly. Tests conducted early in the program proved that this AMTEC design is capable of producing near 30W. A design flaw in the AMTEC converter that reduced its output power surfaced during the final test. Since this test, the design has been modified to improve reliability.

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AMTEC Generator: Phase 1 Propane System

Final Report
September 2001- September 2002

by
J. E. Pantolin

Advanced Modular Power Systems, Inc.

4370 Varsity Drive
Ann Arbor, MI 48108

15 October 2002

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1. Executive Summary

This report covers the work performed for a small Phase 1 program to develop an AMTEC (Alkali Metal Thermal to Electric Conversion) energy conversion based Palm Power generator. A more detailed description of the technology is discussed in the Introduction section. Several organizations and energy conversion technologies are working on a portable power system to replace battery packs and greatly reduce the weight of electrical energy sources carried by soldiers.

The AMTEC converter for this program was developed under an earlier DARPA program and was not optimized for size and weight for the Palm Power goal. The intent of this Phase 1 program was to build a complete system around this converter and in following phases introduce substantially newer designs and approaches to reach the Palm Power specific energy goal. During this program three AMTEC converters were built and tested with one operating at a peak power of 28W while electrically heated. The final converter showed lower power levels of approximately 20W before being placed in the combustion heated system but it dropped off to 5 W during the course of final system integration testing. Investigation of this change uncovered a design flaw that caused the beta"-alumina solid electrolyte (BASE) to crack and this led to internal sodium leaks and the power loss. A design change to correct this flaw and the fabrication of an additional converter was proposed, but ARO determined that no additional funding would be awarded.

AMTEC technology has shown great progress at AMPS in the past few years. AMPS was the lead organization that built the AMTEC converter, assisted in integration testing and packaged the final system. Under this program, AMPS engaged subcontractors specializing in thermal and electronic control systems to assist in designing and building a complete AMTEC propane power generator system. Mesoscopic Devices, LLC was responsible for designing and building the thermal system around the AMTEC converter. This subsystem included a propane burner, a recuperator, fuel delivery and a fan for active cooling. As part of this phase Mesoscopic Devices also investigated ways to build a JP8 combustion based generator. E&M Power, was responsible for the power conditioning and the system function control electronics.

Work on this and similar propane AMTEC generator systems is continuing under AMPS' internal funding. AMPS intends to fabricate a converter modified to correct the earlier problem and incorporate it into the thermal system. This program helped identify design issues that need further development and indicate approaches to the general issues such as reduced system volume, mass and improved reliability.

2. Introduction

The alkali metal thermal to electric conversion AMTEC technology has been described in the literature.[1] It features the ability to produce electric power directly from heat at efficiencies that are better than most other technology options at low power levels (0.5 – 50 watts). A typical converter at about the 5 W_e level is shown in Figure 1. These converters are closed, fully functional systems that need only a source of heat and cooling to produce power. Measured conversion efficiencies for the first generation of converters in Figure 1 at a hot end (at the bottom in Figure 1) temperature of 800°C and a cold end temperature ranging from 250°C to 350°C, are shown in Figure 2. It is expected that these efficiencies can be improved significantly, as the design is refined and the power density is increased.

Figure 1. Typical Converter

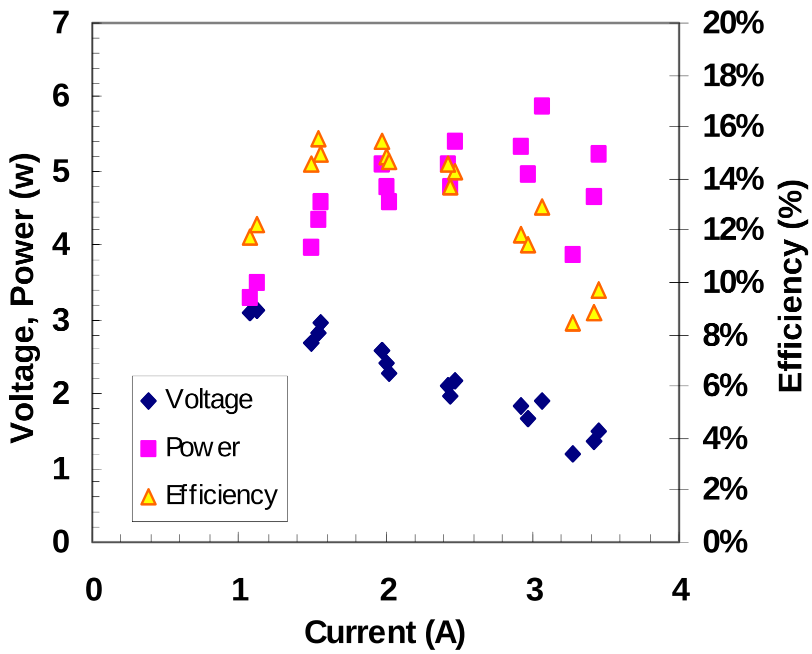

Figure 2. Performance Test Data.

The AMTEC unit in Figure 1 has been installed in a propane-fueled generator, shown in Figure 3. This generator is the first generation of fuel-fired portable power devices. The AMTEC converter is placed in an insulation package, shown in Figure 3 that incorporates a propane burner on one end and cooling fins on the other. This package is then enclosed in the housing, shown in Figure 4. This generator configuration is not optimized and does not include any thermal recuperation, but produces about 5 W and operates for 48 hours on 16 ounces of propane. This generator represents a

Figure 3. 5 W AMTEC Converter in Insulation and Burner Assembly

[1] "Alkali Metal Thermal to Electric Conversion," Robert K. Sievers, Joseph F. Ivanenok, III, and Thomas K. Hunt, Mechanical Engineering Magazine, October 1995, pp 70-75.

starting point in the development of a complete "Palm Power" AMTEC generator, and is currently used as a demonstration of the technology.

Figure 4. 5 W Propane Generator

The converters used in this first generator model are still a relatively new design and have not had any serious long-term life testing. Earlier AMTEC designs, however do have life data. Several converters, of the type shown in Figure 5, were built and tested under an Air Force Program to develop a 60 W AMTEC system for remote sites. A propane burner system, shown in Figure 6, was designed and built by Teledyne Brown Engineering-Energy Systems to accommodate up to twelve of these AMTEC units simultaneously. Converters with design variations were built to investigate the effect of such variations on converter life. Converters operating in burner systems need to use materials that reduce hydrogen in-diffusion from the incompletely burned fuel and will generally incorporate getters in the condenser region to absorb and hold gasses such as hydrogen. Several converters incorporating these features are now on test, with some reaching operating times over 300 days. The normalized power level of 4 converters with the above design feature is shown in Figure 7. The converters started out at different power levels because of other design variations under investigation

Figure 5. AEPS Converter

Figure 6. AEPS Converter Test Bed

in these tests. The initial power levels for these specific converters ranged from 3 to 4.1 watts. Power levels after 300 days of operation, with several start ups and shutdowns, have remained over 75% of initial power (except for one data point associated with an over-temperature transient). Testing continues on these converters.

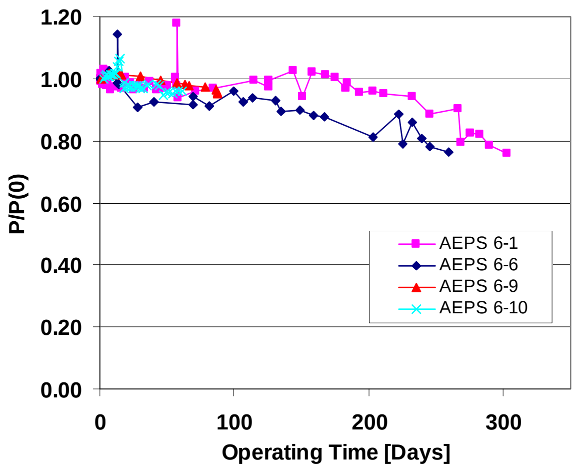

Figure 7. Normalized Power of Four Converters

3. Palm Power Program Objectives

The Palm Power program builds on these initial successes and the potential of this technology. The 20 watt AMTEC Palm Power system design (Figure 8), represents the goal of this development program. For scale, this system is shown next to a typical 20 ounce soda bottle. A bottle of JP8 fuel this size would produce 20 watts of continuous power for over 3 days. This system incorporates a number of advances that were to be developed during the course of the full Palm Power program, including vacuum foil insulation, planar electrolytes and a very small JP8 combustion system. The specific goal of this program is to have a demonstrated, field ready system with a specific energy of 2000-3000 W-hr/kg for 3 and 10 day missions respectively.

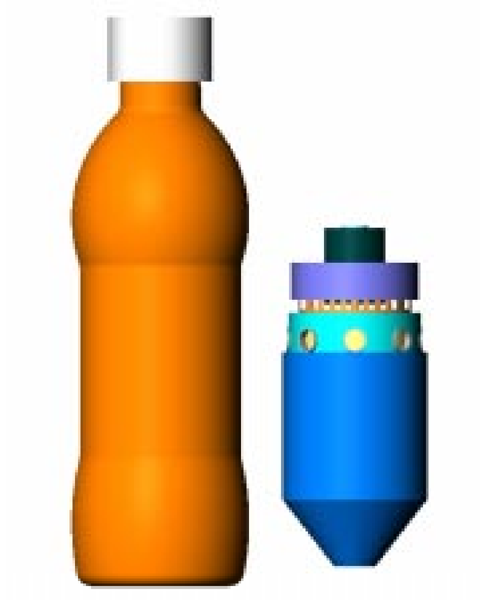

Figure 8. AMTEC Palm Power Generator Next to a 20 oz Bottle

The compact system, shown in more detail in Figure 9, has been designed to meet the Palm Power requirements. Components are tightly integrated to share functions and so keep the system volume as small as possible. The fan, for example is integrated with the electronic components. The insulation and recuperator walls share common structural elements. The vacuum (multilayer) foil insulation is highly effective and maintains the external temperature well below touch temperature limits (with appropriate ventilation). The exhaust gas temperatures can readily be set by the design, starting at about 20°C over ambient. A control system provides for both startup and steady state operation, with a closed loop feedback circuit to keep the converter within proper operating limits for all loads.

A breakthrough electrolyte form, designed to meet the power density target, is a novel “flat tube” or planar design, fabricated with recently developed processes. This new electrolyte configuration permits a much higher electrode area packing density and a much thinner electrolyte wall. One packing configuration is shown in Figure 10. This uses the same basic converter body as the 5-watt converter in Figure 1, but is able to pack 25-watts of power into a shorter hot end section. This increases the power density and efficiency substantially.

Several steps of the fabrication process have already been demonstrated. Plates have been pressed from the beta”-alumina precursor powder and sintered to form the flat

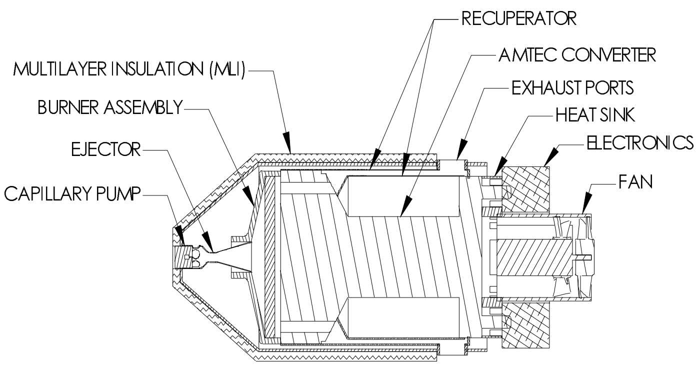

Figure 9. AP^2 System Configuration

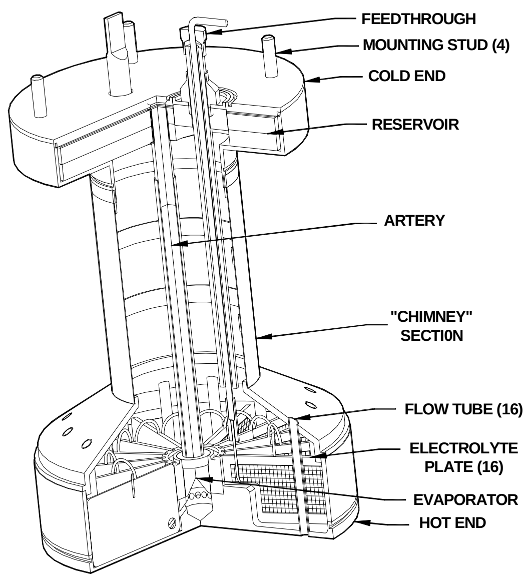

Figure 10. Advanced Converter Configuration

Figure 11. Flat Alumina Tubes with Closed Ends and an Access Hole to the Inside Space

assembly shown in Figure 11 with an enclosed anode space and access to the anode space through the hole in the boss shown. These precursor materials have been shown to be convertible to sodium beta"-alumina electrolyte. The anode space enclosure is illustrated schematically in Figure 12. The two outer faces of this assembly would have active, power producing cathodes. Several more steps are required to fully mature this form. Additional gains in power density will be derived from the use of a potassium-based electrolyte (instead of the current sodium-based electrolyte). Potassium-based electrolytes have been demonstrated in current cylindrical tubular form and have shown either a 50% increase in power at the same temperature relative to sodium-based electrolytes, or a 70°C lower operating temperature for the same power density.

A wick system, with the smaller pores (approximately 1 micron) required for a potassium electrolyte in the AMTEC converter, would be needed to fully execute the potassium-based converter. Material candidates have been identified, but more work is needed in this area. Wick system design, materials and process development tasks still need to be fully defined.

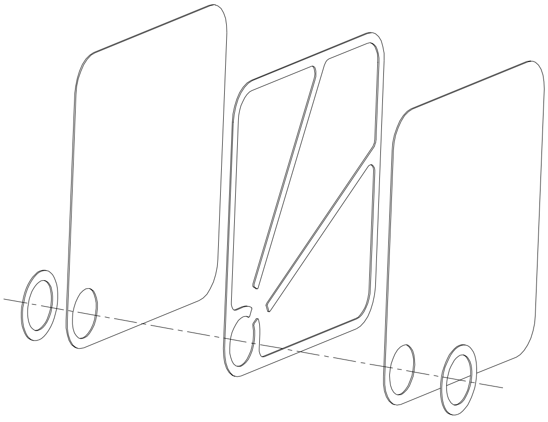

Figure 12. Schematic View of Flat Tube Assembly

4. Development Strategy

The path to a complete and final Palm Power unit is system focused, with the required component technologies developed along parallel paths and inserted into successive generations of system prototypes. Figure 13 illustrates this approach. Table 1 shows how the performance specifications will change with each successive prototype. The specific technology elements to be integrated into each successive prototype are still tentative, so some of the system specifications in Table 1 are still to be determined (TBD). Figure 14 illustrates the performance growth with each new system. The system focus of this project, allows the components that are under development to be constantly assessed relative to system needs. Because this is a highly integrated system, it is critical to understand how all the subsystems work together, so that the requirements for the components can be identified as completely as possible as early as possible. This reduces the development effort and provides a measure of progress toward the ultimate system target.

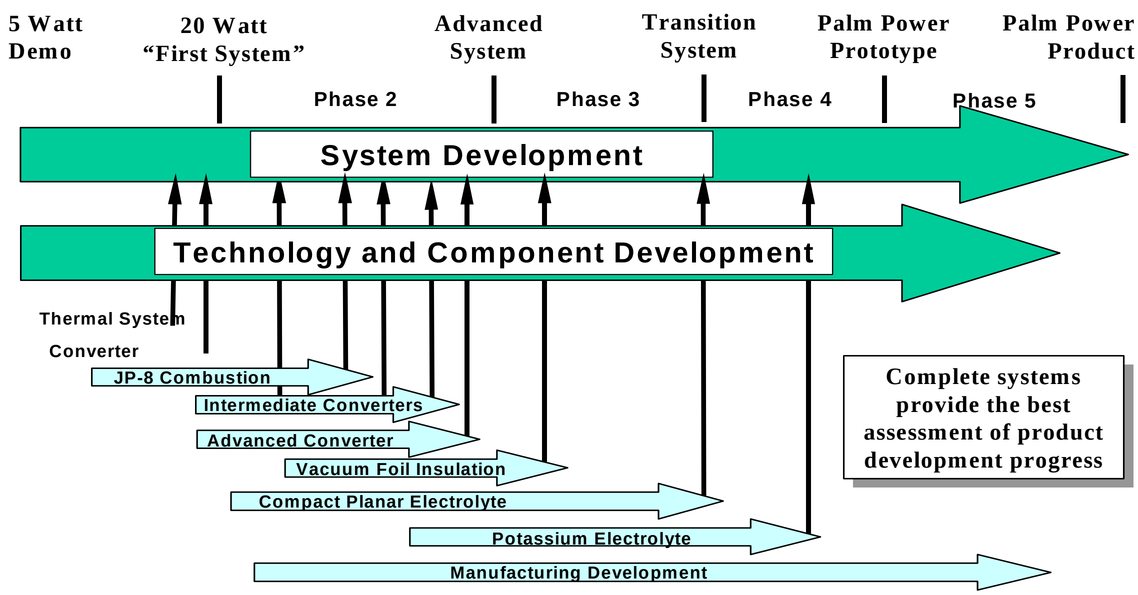

Figure 13. Technology Development and System Level Integration Strategy.

5. "First" System Design

The first prototype to be developed in this program will actually be the first complete, fully integrated, fuel-fired AMTEC system. The 5-watt generator that is currently used for performance demonstrations still requires manual startup, fuel, and load control. The generator now under development to succeed the 5-watt demonstration unit, will incorporate automatic control of all these aspects. The performance specifications are shown in Table 1. Generator features are outlined in Table 2.

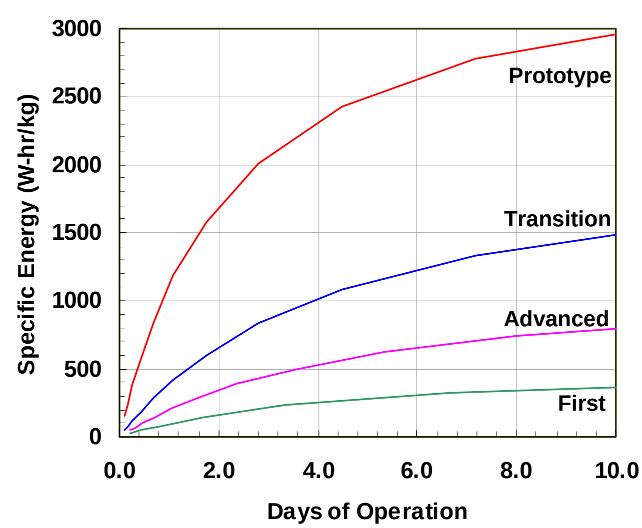

Figure 14. AMTEC Palm Power Prototype Performance

The general layout of the first system is shown in Figure 15. This design uses the same type of housing

as the 5-watt generator, shown in Figure 4. Fuel enters a standard fuel quick-connect on the left side and power is processed and provided to the user on the right side. A detailed design view of the burner, thermal, blower and heat rejection systems is shown in Figure 16. The perspective in this view has been reversed relative to the orientation shown in Figure 15. A system schematic is shown in Figure 17.

Table 1. System Specifications for Successive AMTEC Generator Prototypes

Specification	5 Watt Demo	First System Phase 1	Advanced System Phase 2	Transition System Phase 3	Palm Power Prototype Phase 4
Power Output (W)	5	20	20	20	20
Voltage (V)	2-3	12	12	12	12
Fuel	Propane	Propane	JP8	JP8	JP8
Fuel Consumption Rate (g/hr)	10	27	TBD	TBD	6
Weight (kg)	2.1	5	2 (est)	1 (est)	0.3
Dimensions (in)	5 x 5 x 14	5 x 5 x 22	TBD	TBD	2.5OD x 4
Exhaust Temperature (°C)	120	120	80	65	65
Noise	No fan	Low	Low	Low	Low
Start-Up Time (min)	10	60	TBD	TBD	5
Specific Energy (W-hr/kg)	200	350	800 (est)	1500 (est)	2-3000

Table 2. First AMTEC Generator Features

Commercial Propane
12 V regulated output
Automatic start-up with fault detection. System ready and fault indicators.
Load follow control system
Internal battery for ignition and fan for start-up. Includes charging circuit for battery.
Housing for handling and transport, not ready for all field drop tests
Operating environment range -20°C – 40°C, Sea level – >5000 ft

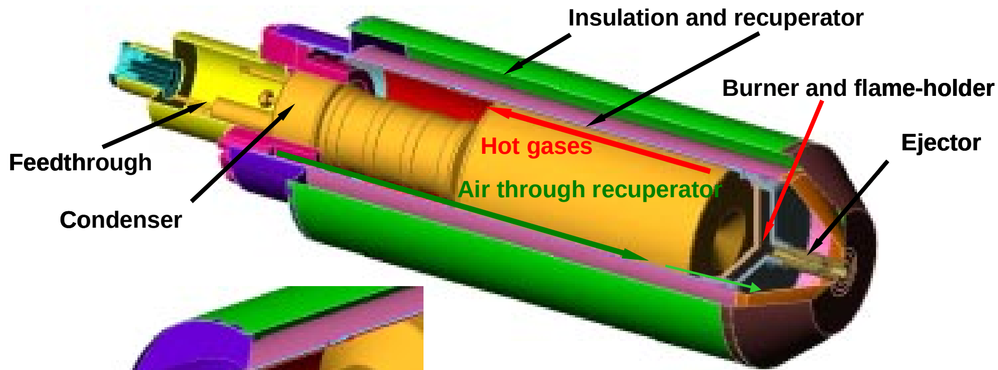

Figure 15. Layout of Complete Thermal System

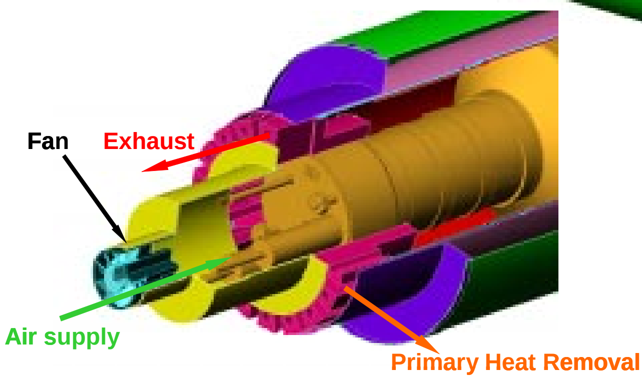

Figure 16. Layout of Complete Thermal System, Including the AMTEC Unit

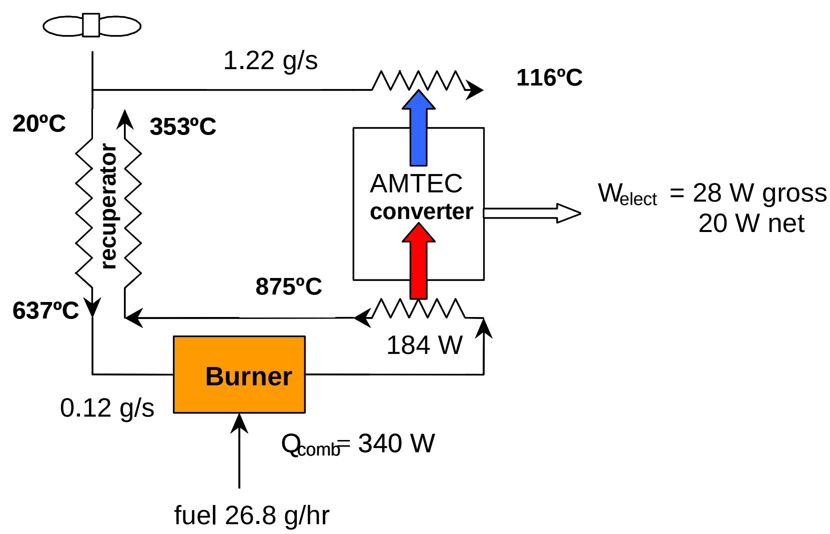

Figure 17. First System Schematic

The air enters the system through the fan and is split between the AMTEC cooling stream (90%) and the combustion air (10%). The combustion air is heated as it passes through the recuperator wrapped around the AMTEC body. The air is mixed with fuel, burned to heat the AMTEC body and the hot combustion gasses flow back out through the inner channel of the recuperator. The combustion products are mixed with the condenser cooling gases and exhausted from the system. An aerogel insulation package is wrapped around the burner and recuperator to minimize the parasitic heat losses. (The heat loss through the insulation is expected to be around 100 W. This is still high, relative to final targets, which will have to be and can be achieved with vacuum foil insulation.)

6. System Modeling

The analytical model includes the recuperator, a combustor, a simplified model of the AMTEC converter, and heat lost through the insulation. Results for system temperatures and mass and heat flows for this model are displayed on the diagram in Figure 17 and shown graphically in Figure 18. The primary model inputs include:

- Converter dimensions, converter output and efficiency as a function of hot and cold end temperatures (based on GF Model 1 data provided by AMPS),
- Recuperator and insulation package dimensions,
- Material properties (thermal conductivity of wall and insulation materials, permeability of flame holder) and fluid properties (air and exhaust conductivity, viscosity, density, and fuel heating value)

The model calculates the temperatures at several points in the system (air entering the ejector, combustor temperature, exhaust gas entering the recuperator, exhaust gas leaving the recuperator) based on the fuel flow rate. Overall efficiency is defined as the converter electrical output divided by the flame power. This neglects any losses in the electronics or parasitic loads (such as the fan and other powered components in the system).

6.1 Recuperator and combustor

The recuperator is a two-channel, annular configuration, laminar, counterflow heat exchanger. Air inlet is at the cold end of the converter in the outer channel. Air is entrained into the ejector, mixes with the fuel, flows through the flame holder and combusts. The exhaust gas leaves through the inner channel of the recuperator. The recuperator active heat transfer length is equivalent to the large diameter section of the AMTEC converter. The flame holder is a silicon carbide porous mat. Combustion can be either blue flame or radiant, depending on the fuel flow rate.

6.2 Insulation

The insulation package surrounds the recuperator outside the AMTEC converter, as well as extending around the combustor and ejector. The insulation assumed in this model is the aerogel from Nanopore used in the device. We have used properties for aerogel at ambient pressure conditions, as we believe that a vacuum could be difficult to maintain for the life of the system. Heat lost through the insulation is included in the model as a reduction in the exhaust gas temperature immediately before the exhaust gas enters the recuperator. This should be a conservative estimate.

6.3 AMTEC Converter

For this model, we used data provided by AMPS from the GF Model 1. Curve fits were generated for the converter electrical output and converter efficiency as a function of hot end temperature for cold temperatures of 250, 300 and 350°C. Only data from the 300°C temperature is displayed in Figure 18.

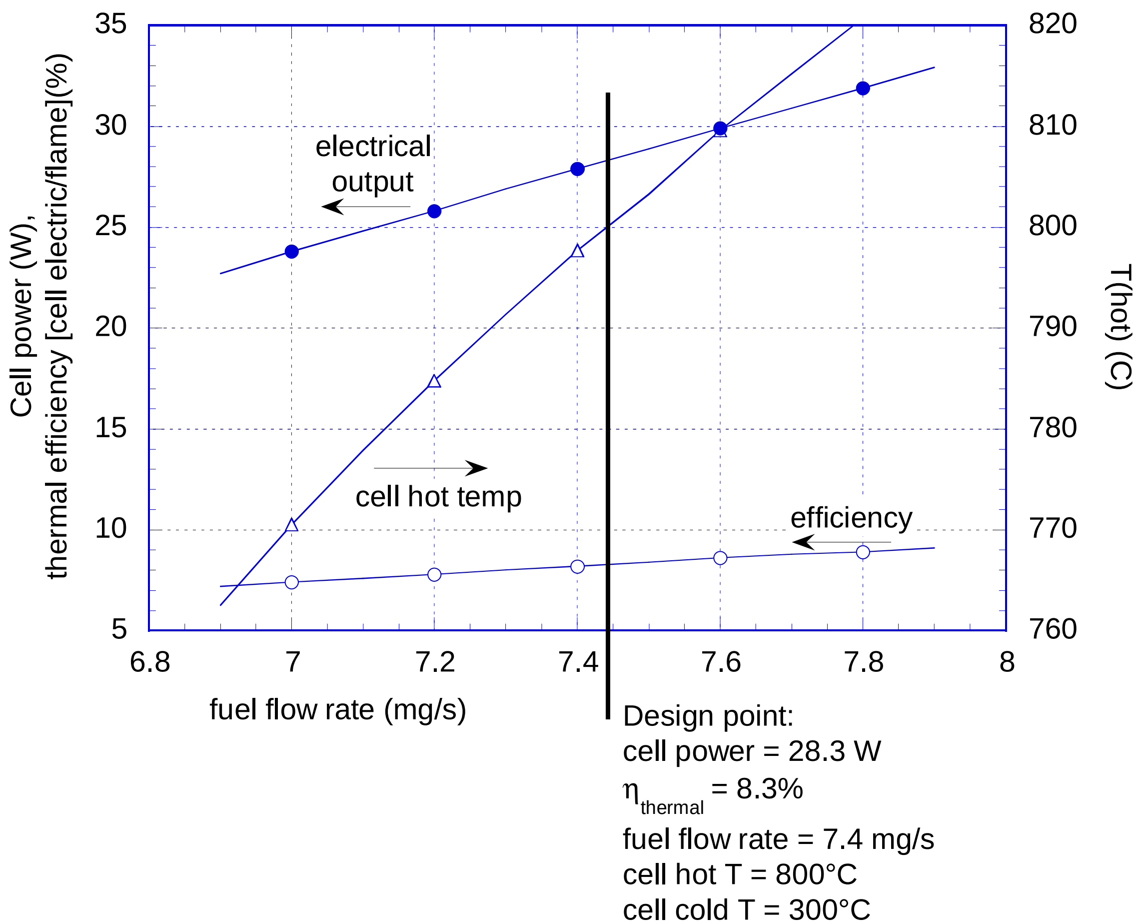

Figure 18. Model Predictions with a 28W Gross AMTEC Converter, 27 g/hr, 8.3% Overall Efficiency

7. AMTEC Design and Testing

The first AMTEC converter designated as GF (for gas-fired) was built and tested in 2000, prior to the start of the Palm Power program. This converter, designated as GF-1A, was developed as part of an earlier DARPA program, and was intended to be a test bed for advanced AMTEC electrolyte tube development. This converter used relatively large BASE tubes because it was testing elements intended for a 500 watt system. This converter was a working AMTEC unit operating at the power levels targeted by the Palm Power program. This converter design therefore became the baseline for incorporation into the first AMTEC generator.

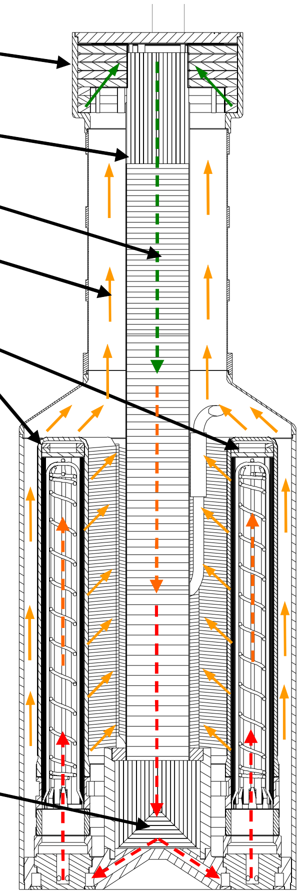

Figure 19. GF Converter Design Layout and Sodium Flow Path

The converter layout is shown in Figure 19. The condenser has a wick that contains the reserve sodium in liquid form. Sodium is wicked from this condenser reservoir, through the artery and to the evaporator. There the sodium liquid evaporates and flows as a vapor into each of the 8 BASE (beta"-alumina solid electrolyte) tubes. The sodium condenses on the wick inside each BASE tube, providing both the anode (in liquid form) and a heat pipe fluid to transport heat from the hot (lower) end of the converter up into each BASE tube. The sodium atoms inside the BASE tube give up an electron to the anode current collection system, and then pass through the BASE tube as ions. The sodium ions arriving at the outer surface of the BASE tube recover an electron at the cathode, become neutral sodium atoms again, and then evaporate and flow as a vapor back to the condenser. The BASE tube cells in the converter are connected in electrical series, providing a nominal 2 – 3 V at peak power.

Figure 20. Assembled GF Type Converter

7.1 Palm Power AMTEC Converters

Three AMTEC converters were built under this program. Table 3 has a list and summary of each one. The first one in this table (GF-1A) was built prior to this program, operated reasonably, and served as the pathfinder for this new design. Each successive unit performed better and had more stable operation than those previous. GF-1B was the first in this program. It was built to verify operation of the basic design, but was not designed for burner operation or to fit in the final generator package. GF-2A included the Haynes alloy for low

hydrogen permeation in a flame heat source, but it lacked the low profile electrical feed-through design required to reduce packaging size. More detail about the feed-through work is discussed later in this report. The final converter fabricated was GF-2B as shown in Figure 20. It contains all the design elements to fit with the other system elements and produce the required power for the Palm Power goal.

Table 3. Summary of GF Converters.

ID	Date	Results
GF-1A	9/00	Fabrication pathfinder exposed materials issues. Demonstrated proof of concept. Maximum power of 20 W, but not stable. Sodium wick issues identified.
GF-1B	9/01	Resolved materials issues. Improved power output, but still not stable. Still suspected the artery wick, but also the sodium distribution balance in the wicks of each BASE tube.
GF-2A	12/01	Advanced Haynes alloy successfully introduced. Demonstrated output power above 28 W. Stable power, but degraded after a month on test. Performance characterization for integration into generator. Stopped operating after 2 months of testing.
GF-2B	3/02	Stable but lower performance. Only reached 20 W. Installed in generator for initial integration testing and produced 6W. A failed BASE tube assembly suspected.

7.2 Converter Performance GF-2A & 2B

The data from the last two converters built are of the most interest. The difference between them is the electrical feed-through design. A longer lower temperature design was used in GF-2A while the development work was completed for the final feed-through design. Of the converters of this basic

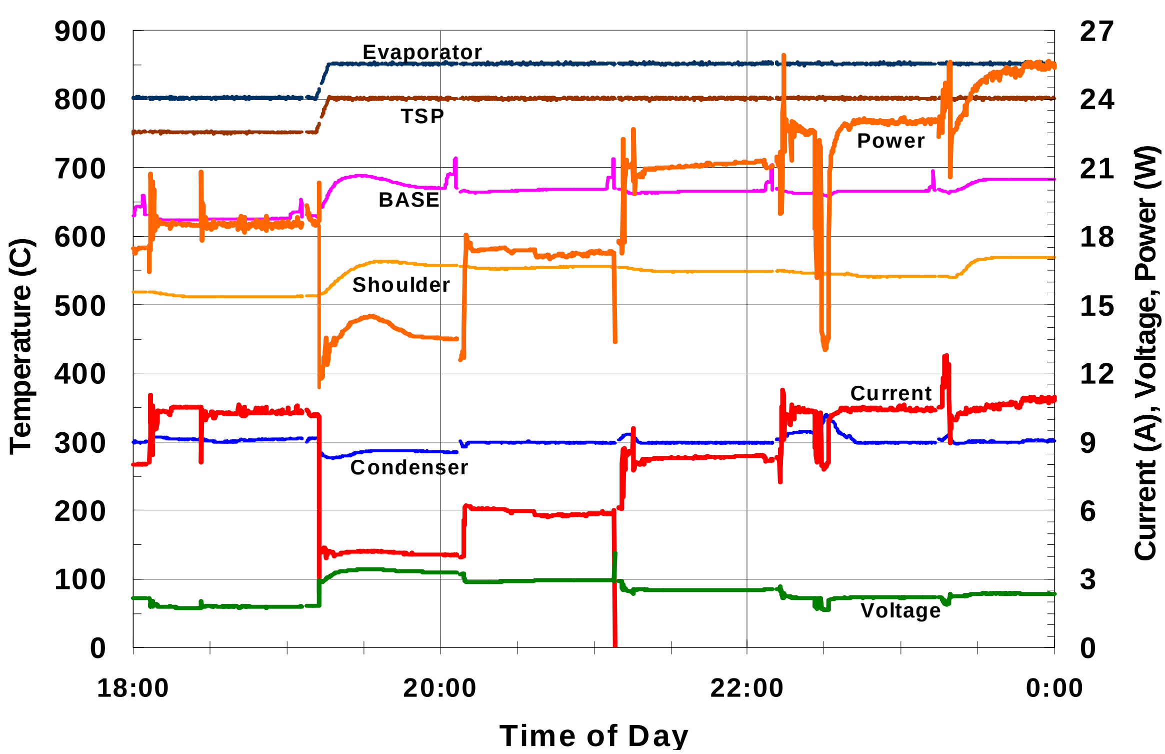

Figure 21. Electrically Heated GF-2A Performance Data

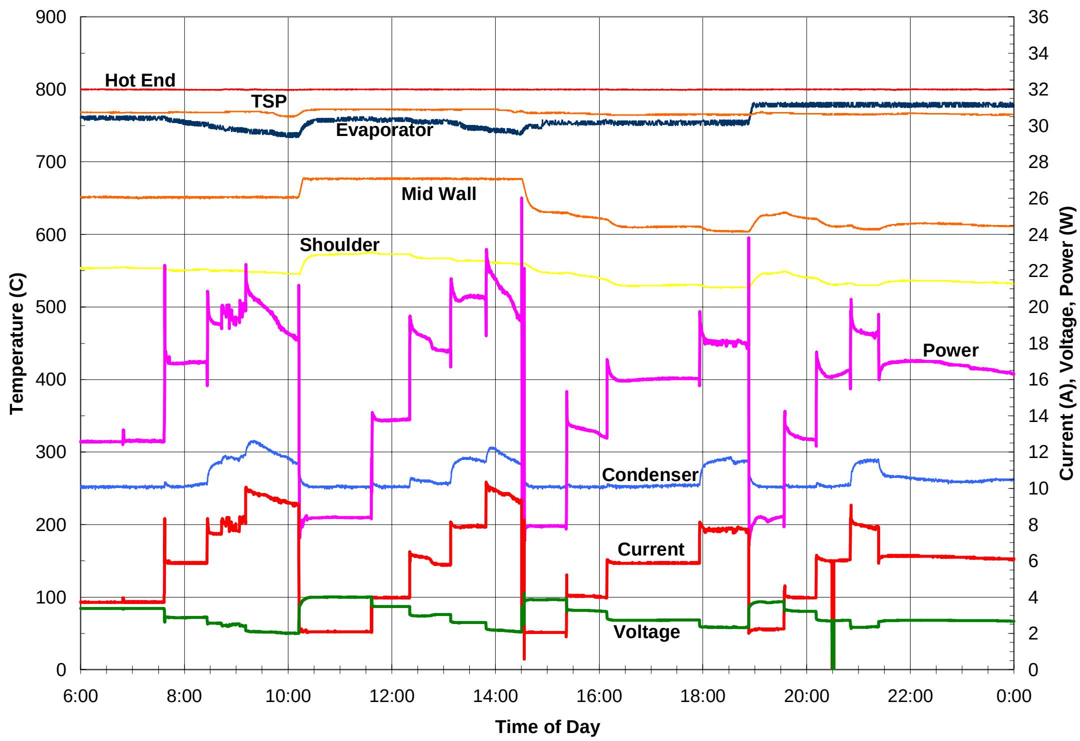

Figure 22. Electrically Heated GF-2B Performance Data

design, GF-2A had the highest initial output power at 28W with subsequent tests yielding 25W as shown in Figure 21. This however did not last long and the converter eventually stopped operating. The cause of this was not investigated until a later date.

The third converter, GF-2B, was intended for integration into the generator system. It did not reach the same power level as 2A and produced only about 20W peak power as shown in Figure 22. Although the cause for the reduced power level was not known, integration testing continued assuming that the system would also have a lower final power level. The unit was shipped, for integration testing, to Mesoscopic Devices, the subcontractor responsible for supplying the insulation, burner and recuperator package where it was assembled in the package for testing. It was slowly heated with the propane burner to operating temperatures. From the start, it appeared that the converter performance was much lower than in the previous testing. It was held at 700°C for some time and then the hot end temperature was increased to above 800°C. A plot of the data from this test is given in Figure 23 along with power output of approximately 4W continuous and just over 5W peak.

7.3 Performance Investigation

The 2B unit was returned to the AMPS facility where it was operated with electric heating to check its performance. At this time it operated at a 6W level and remained constant. The cause of this change in performance in 2B and the stoppage of 2A there was the immediate subject of an investigation. This was only the fourth converter of this design ever built and not all of the issues of its operation were known. The candidate for a “Post Test Analysis” was the 2A unit since it was not functioning. It was placed in an argon atmosphere glove box where it was cut into sections for inspection. The BASE tubes (converter cell elements) were cut out and the wire wrap and the current collection screen were removed. Several of the tubes were then seen to have cracks in the BASE material with signs of sodium leakage and the cracks coincide with the solid niobium-1%zirconia rods used as interconnects between the series connected BASE tubes. A typical crack is shown in Figure 24. These cracks could easily account for the drop off in performance observed in this converter. Cracks of this nature will result in a lower and even no pressure

drop across the BASE material resulting in little and possibly zero power producing capability. From the shape and location of the cracks, it was clear that the solid rods strapped against the BASE tubes were causing the cracks. An example of the rod current collector design is displayed in Figure 25. To solve this the rods were eliminated and replaced with fine wires that are braided together as shown in Figure 26. Since this design change no other GF converters have been completed though efforts are currently underway to build a converter with this modification.

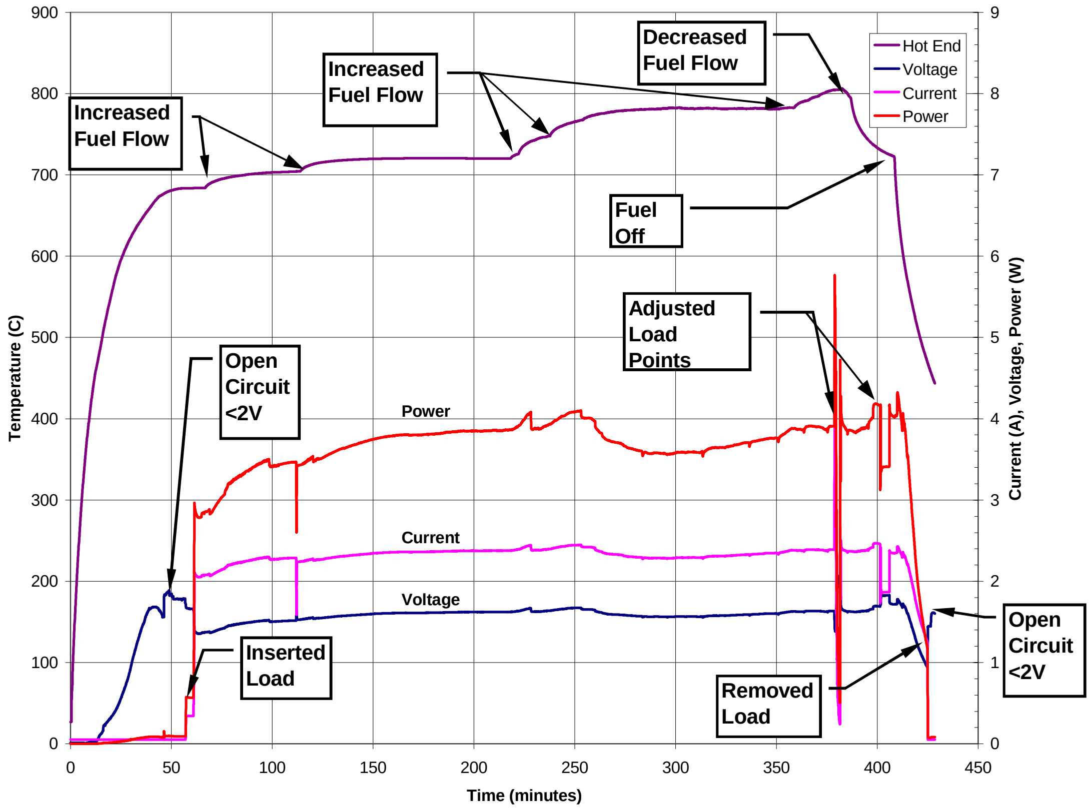

Figure 23. Combustion Heated GF-2B Performance in System

Figure 24. Crack Observed in BASE Tube

Figure 25. Rod Attached to BASE

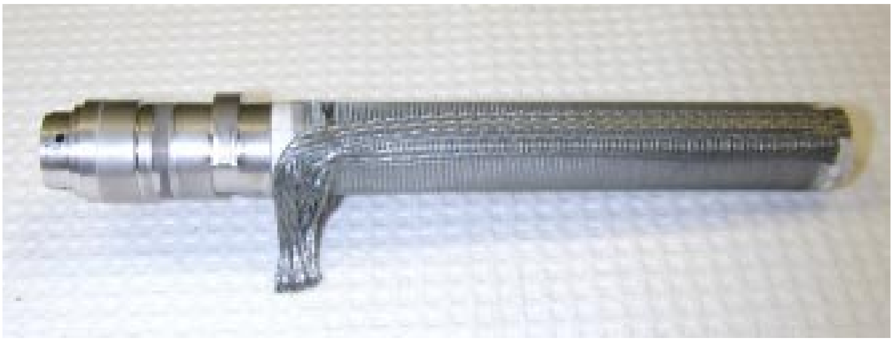

Figure 26. New Flexible Buss Design

8. Sub-System and Component Development

8.1 AMTEC Power Feed-Throughs

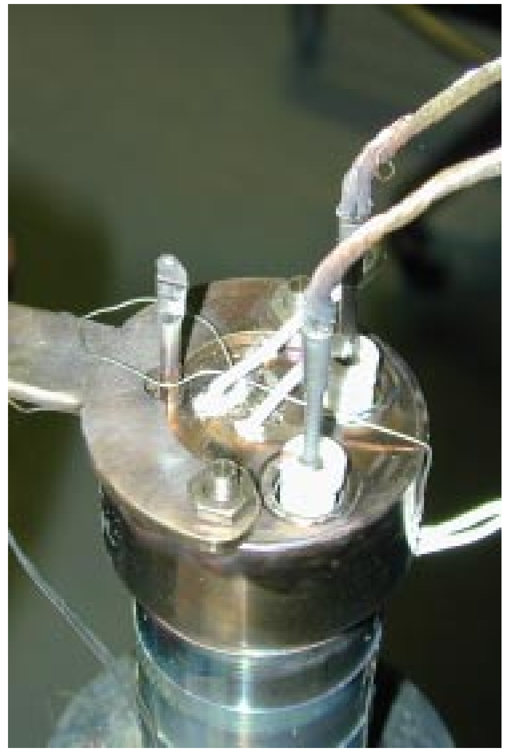

Figure 27. Feed-Throughs in Assembled Converter

Electrical power feed-throughs are a critical component of AMTEC converter design. Requirements for an electrical feedthrough are: electrically insulating, hermeticity in a sodium environment on one side and air on the other at temperatures up to 400°C, physically robust and have high electrical conductance. Electrical insulation typically requires a non-conducting ceramic material and these are by nature fragile. The ceramic then needs to be joined to metal components by methods of brazing that tend to make the assembly even more fragile.

Figure 28. Feed-Throughs During Assembly Stage

AMPS currently has developed a proven feed-through design for a 10 amp maximum current capacity. The Phase 1 Palm Power AMTEC converter required a 30 amp feed-through that had to be developed. The goal for this development was to reduce the cost of each feed-through and to produce robust components sized for this AMTEC converter power. A reliable high current feed-through has now been developed and it was used in the GF-2B converter shown in Figures 27-29. Its design is low in profile by putting much of it inside the converter. Flexible stranded copper leads are attached during the assembly operation providing low resistance connections to the power processing electronics as well as minimal parasitic losses. Examples of the final feedthrough design are shown in Figures 27 and 28.

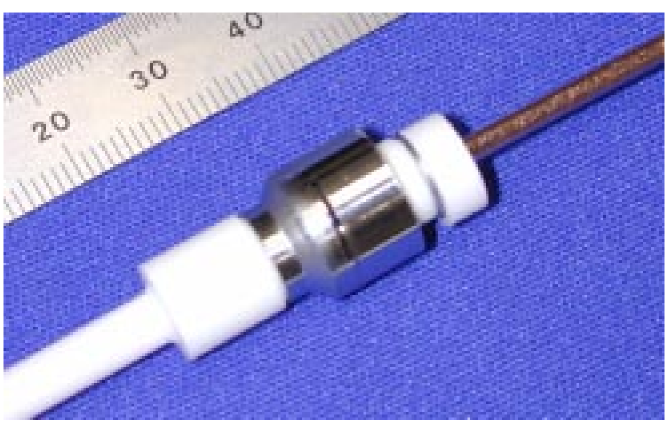

Figure 29. Close-up of Feed-Through

8.2 System Burner

A flame holder sits in the base of the burner and spreads the fuel and air mixture over its surface. AMTEC related burner work prior to this program used a reticulated metallic flame holder. These metallic flame holders degraded after a short time at the operating temperatures in excess of 800°C. In order to extend the life and increase the reliability an alternate material or a significantly modified design was needed. Silicon carbide fibers bonded into a mat that can be cut into the desired shape was found to be

Figure 30. Burner and Flameholder Test

used in radiant burners. In Figure 30 a SiC mat is shown holding a flame. This burner produces as much as 900 W of heat and operates in blue flame and/or radiant modes.

8.3 JP8 Burner Options

As part of this program, a plan to develop a JP8 burner for an AMTEC generator was explored. There are two current fuel delivery options for JP8: a small electric pump or a capillary pump system with vaporizer. These are shown in Figures 31 and 32. This would be the starting point for further development and any progress on small JP8 burners could be useful both for AMTEC Palm Power and other conversion technologies that can take advantage of heavy fuel burners.

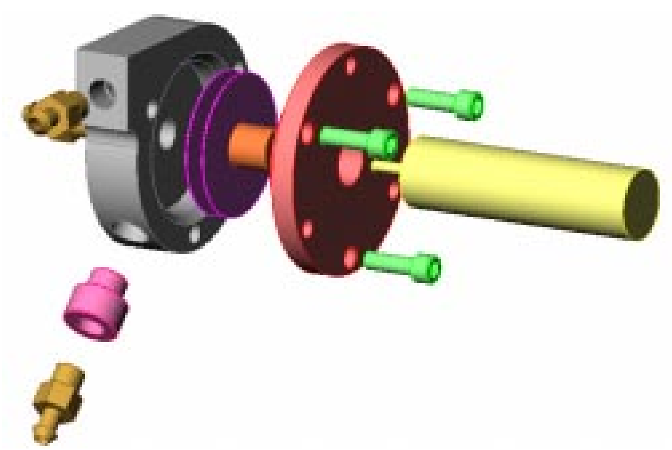

Figure 31. Illustration of Liquid Fueled Option, Rotary Pump with Vaporizer.

Figure 32. Liquid Fueled Option, Capillary Pump with Vaporizer

8.4 Fuel Control

A solenoid valve was selected to control the fuel flow to the burner. This valve is quite small and is shown in Figure 34. The control electronics software has a temperature control loop that monitors the burner thermocouple and varies the pulse width or open time of the valve. The on time of this operation can also be described as the “Duty Cycle” and it is referred to in

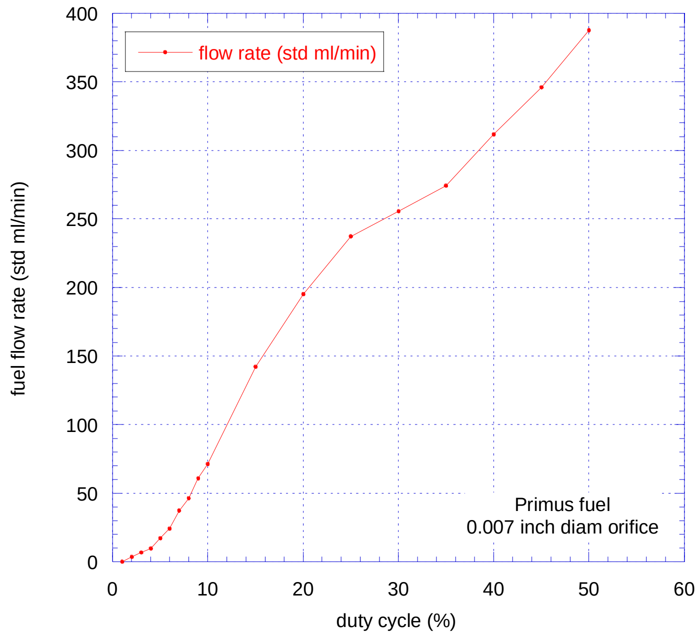

Figure 33. Fuel Flow Rate of Solenoid Valve vs. Duty Cycle

Figure 33. The manufacturer of the valve recommends a spike and hold circuit that initially supplies a high "spike" voltage to open the valve, and then a lower voltage to keep it open. This reduces the heat in the valve and the power required to operate it. Tests show that the operating power in the fuel flow range required to heat the AMTEC converter is less than 0.5 W.

8.5 System Fan

Another component of the thermal package is a small fan. The fan is required to remove sufficient heat from the AMTEC converter and to force the incoming air through the recuperator into the burner. A tube-axial fan was selected, shown in Figure 35, based on the pressure drop through the system and the required air flow. A lean burning flame is desired both during startup and in steady state "hot" operation. In order to meet all these requirements, a slightly larger fan was selected to provide an extra margin of control. There are still some uncertainties in the system design, so an oversized fan can be cut back in flow with the control software and minimal control electronics.

Figure 34. Solenoid Fuel Valve

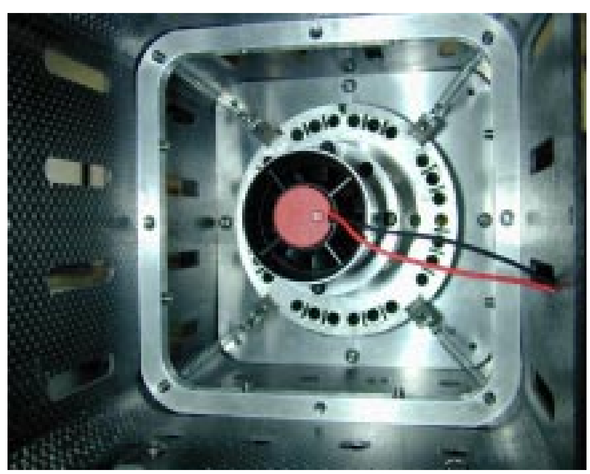

Figure 35. Fan in System

8.6 Electronics

The AMTEC generator has two main electronic systems: power processing and system control. Power processing takes the AMTEC output which varies from about 2 to 4 volts DC, and steps it up to a higher voltage. In this design the output voltage of the system was set at the widely used 12 volts.

8.6.1 Power Processing

There are many DC-DC converter (power processing portion) designs for various applications. There are commercially available integrated circuits for low power applications in the sub watt to several watt

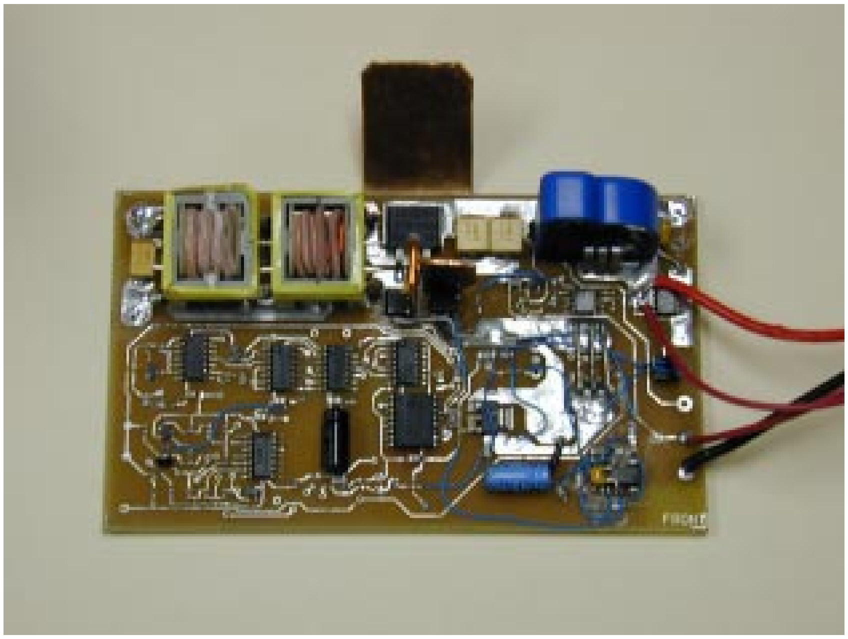

Figure 36. 25 W DC-DC Converter Breadboard

range. These typically have conversion efficiencies greater than 80 percent with input voltages as low as 2 volts. Going to higher power levels, i.e. more than 10 watts, increases power loss in the switching transistors but increasing the input voltage improves the voltage up-conversion efficiency. Figure 36 is the 25 watt DC-DC converter breadboard designed for the AMTEC generator. It was designed to operate at an input voltage of 2.5 V, at the estimated peak power point of the AMTEC converter and put out 12 volts. Table 4 displays some typical data points of this breadboard and shows conversion efficiencies of 78% with a 2.5V input. Note that the efficiency drops as the input voltage decreases and this circuitry is capable of handling power levels of over 30W.

Table 4. DC-DC Converter Data for First Round Testing, 2.5V Peak Power

Vin (V)	Iin (A)	Vout (V)	Iout (A)	Pin (W)	Pout (W)	Eff. (%)	Load (ohms)
2.43	2.65	11.98	0.39	6.44	4.67	72.56	30.72
2.50	7.26	11.97	1.19	18.16	14.24	78.42	10.06
2.46	9.36	11.97	1.51	23.03	18.07	78.47	7.93
2.38	14.06	9.85	2.46	33.50	24.23	72.32	4.00

In testing the GF-1B converter, it was determined that its peak power occurred closer to a potential of 2.0V. To match the DC-DC circuit board to the AMTEC converter better, the circuitry was modified to optimize at a lower input voltage of approximately 2.0V. The data is shown in Table 5 at two different loads. Both tables, show that higher input voltages increase the efficiencies and the design of power conditioning circuits need to be matched to the load to reduce system losses. Higher converter output

Table 5. DC-DC Converter Data with Modifications for Lower Input Voltage of Breadboard

Vin (V)	Iin (A)	Vout (V)	Iout (A)	Pin (W)	Pout (W)	Eff. (%)	Load (ohms)
1.53	12.15	11.16	1.08	18.59	12.05	64.84	10.33
2.51	7.21	11.99	1.18	18.10	14.15	78.17	10.16
2.25	8.23	11.98	1.17	18.50	14.02	75.76	10.24
2.00	9.59	11.98	1.17	19.18	14.02	73.08	10.24
1.54	12.06	11.26	1.10	18.51	12.39	66.91	10.24
2.50	11.51	11.97	1.85	28.75	22.14	77.02	6.47
2.26	13.67	11.97	1.84	30.87	22.02	71.35	6.51
2.24	13.84	11.97	1.84	30.96	22.02	71.14	6.51
2.17	14.87	11.96	1.84	32.21	22.01	68.32	6.50
1.65	16.43	10.28	1.58	27.04	16.24	60.06	6.51

voltage would require more AMTEC cells connected in series or several converters connected in series. At this time none of these converters operate at voltages greater than 4 volts and the peak power operating points are at lower voltages.

Figure 37. Completed Control/Power Board

8.6.2 System Control

A completely automated control system was designed for this generator, Figures 37 and 38. Previous systems used a manually operated fuel valve to control the temperature of the burner. This Palm Power AMTEC generator has sufficient hardware and flexible software to allow changes to the operating sequences and parameters as the generator behavior becomes better understood. This control system has buttons to initiate the startup and shutdown sequences. Any deviations from the parameter check list during startup defines a fault and the red error indicator is then illuminated and the controller goes into shut down mode. If the proper operation is verified, the generator will be at operating temperature and the green system indicator is illuminated. To shut down the generator, the stop button is pushed to turn off the burner, the load is disconnected and the system cools down with the fan operating for a short period.

Figure 38. Back Side of Control/Power Board

Hardware functions of the control system include: a temperature control loop that monitors a thermocouple voltage and changes the pulse width modulation to the fuel solenoid, an AMTEC voltage monitor that turns on the DC to DC up converter when the AMTEC voltage reaches 4 volts, a fan speed control if it is desired to cut down standby power, a circuit to turn on the igniter and shut down power to it when the burner is successfully lit, a tri-color LED for system indicator and an LCD display panel showing AMTEC voltage and temperature. Also included is a small rechargeable battery pack that is capable of operating the control system and fan while the generator system heats up and before it starts producing power on its own. All these system functions were tested earlier in the program with the controller breadboard shown in Figure 39 before the final board fabrication. At the conclusion of this program, limited system testing of the final hardware was

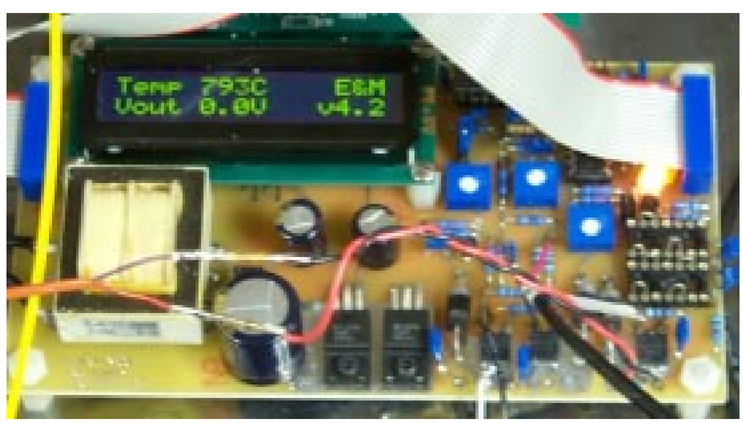

Figure 39. System Controller Breadboard for Integration Testing

conducted but it was sufficient to verify all system elements.

8.7 Housing Design

The design goal for this Phase 1 program was to deliver a reliable and easy to operate table top demonstration unit. It is possible to just attach the fuel bottle and hit the start button. Figure 4 shows the 5 W generator built prior to this program. It is this smaller and less developed system that helped to set guidelines for the design of this higher power producing generator.

The generator system is enclosed in a carbon/epoxy tube approximately 22 inches long by 5 inches square with aluminum end caps. A strap can be attached to the ends for carrying the generator. Fuel is delivered through a quick-connector located on the burner end of the generator. The other end cap has a power connection, display panel, status LED and a start and stop button. A general layout is shown in Figure 40 and the actual system is in Figure 42.

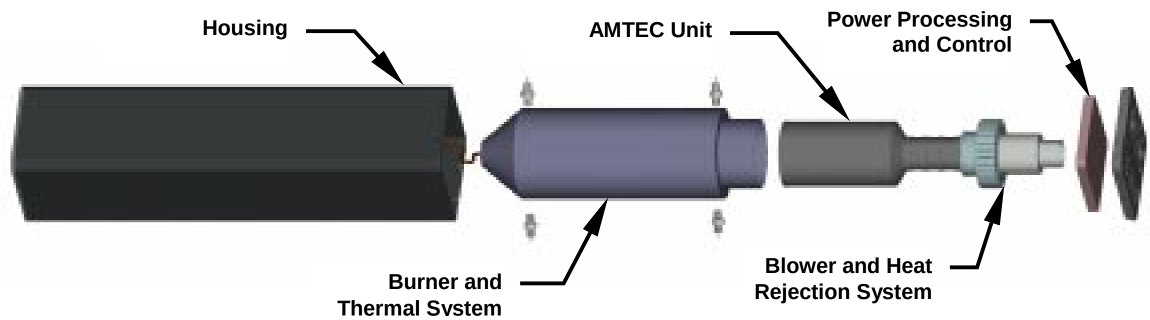

Figure 40. First AMTEC Generator System Layout

Fabrication of the housing is simple. The tube is made on a square mandrel by placing layers of carbon fiber cloth on the tube. The cloth is then impregnated with epoxy and pressure plates are placed on all four sides. It is allowed to cure and then removed from the mandrel. Holes are machined to attach the

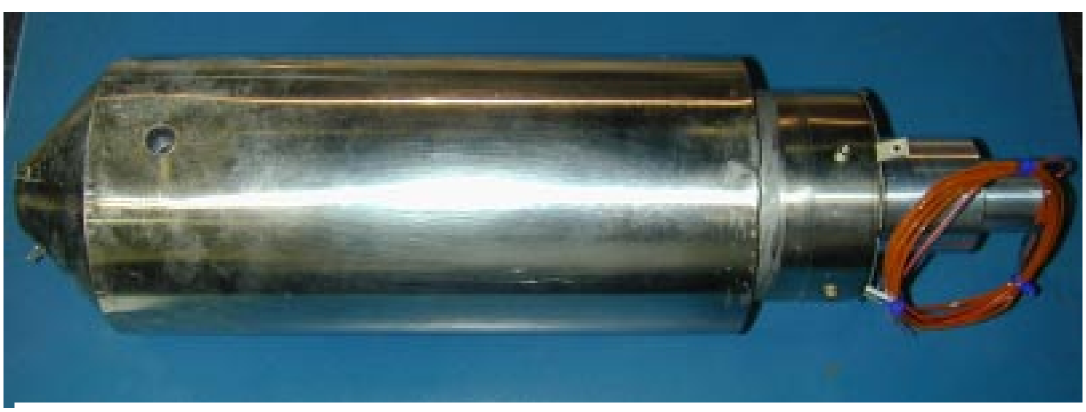

Figure 41. Burner and Thermal System with AMTEC Converter Inside

end plates and additional holes are made for ventilation. The end caps are anodized machined aluminum. Additional rings will fit inside the tube and the converter and thermal system attaches to these rings for support. The actual burner system with the AMTEC converter is shown in Figure 41 and it has attachment points for springs that hold it in place inside the housing as shown in Figure 43.

Figure 42. Generator with GF-2B Converter

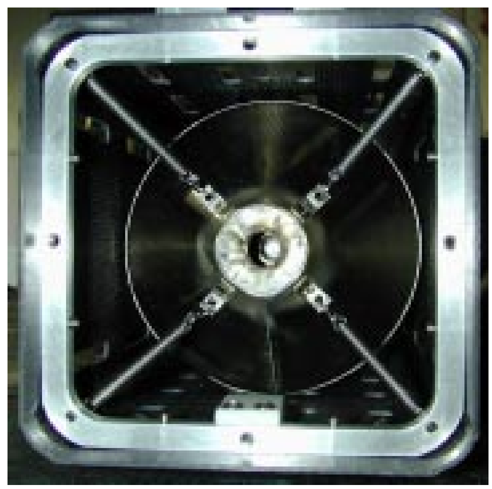

Figure 43. Hot End View of Generator with Spring Suspension

9. Conclusions

AMTEC's heat source flexibility makes it a good candidate for an electric generator designed around a combustion heat source. This first system uses propane but it can eventually use other fuels like JP8. This program brought the design very close to a complete operating system and emphasized that weight and size are still issues that will require breakthrough designs such as the planar tube concept discussed above to reduce weight and volume to the Palm Power criteria levels. Table 6 was the running check-list during the program and gives a summary of where particular issues and specifications are at the end of the program.

Table 6. Detailed Milestones and Metrics of Program

Task	Milestone	Metrics	Date	Lead	Status
Specifications	Draft Subsystem Specifications	1. Approved document	10/26/01	AMPS	APG-20 Product Specification, Rev B completed.
	Specification Freeze	1. Approved document	1/2/02	AMPS	Revision 1 completed.
Thermal System	Valve Specifications	1. Meets flow control requirements	10/19/01	MD	Completed
	Design Review	1. Performance predictions	11/27/01	MD	Completed
	Thermal System Demo (using converter mockup)	1. Combustion system reaches target converter temperature 2. > 10% excess air 3. Fuel flow and temp control at set point	2/1/02	MD	Completed
AMTEC Converters	Complete GF-1B Testing	1. > 22 Watts power output 2. Thermal performance data to use in design reviews	11/21/01	AMPS	Measured power output of 24 W. Thermal data delayed for next converter.
	GF-2 Design Review	1. Release design for fabrication	11/27/01	AMPS	Completed.
	GF-2 Testing	1. > 28 Watts power output 2. Thermal performance data	2/1/02	AMPS	Completed, at 20W during early life
DC-DC Converter	Breadboard Evaluation	1. > 70% efficiency at specified design point	11/27/01	E&M	Completed, near design spec.*
	Final Hardware	1. > 75% efficiency at operating point 2. Fits to housing	7/29/02	E&M	Completed
Control System	Concept Design	1. Review determines that design will provide specified function	10/25/01	E&M	Completed
	Fuel Flow Control Trial	1. Provides flow control over design range	1/25/02	E&M	Completed
	Final Hardware	1. Controls converter at target operating temp 2. Fits to housing	7/29/02	E&M	Completed
Housing	Design Review	1. Design meets requirements	1/2/02	AMPS	Completed
	Final Fabrication	1. Supports all components 2. Provides required user interface	6/7/02	AMPS	Completed
System Fabrication	System Testing	1. > 20 Watts at 12 V 2. Self regulating 3. 20 g/hr fuel consumption 4. < 4 kg	6/15/02	AMPS	1. <5W at 12V [2] 2. Completed 3. 27g/hr calc. 46 g/hr measured[3] 4. 5 kg

* measuring 68% efficiency

[2] Based on present performance of GF-2B after damage

[3] Based on model predictions, measured data with damaged AMTEC converter. See also Figures 17, 23